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(54) Fourier spectrometer

(57) A Fourier spectrometer with an amplitude splitting interferometer has a polarizing device 3 for the linear polarization of a parallel light beam, a birefringent delay element 4, an optical wedge configuration 5 of birefringent material consisting of a fixed and a moving optical wedge 6, 7 and an analyzing device 10 with a transmitting orientation preferably rotated by 90 degrees with respect to the polarizing device. As viewed in the propagation direction of the beam, a retro-reflector 15 is provided for behind the optical wedge configuration 5 which reflects the light back through the optical wedge configuration and the delay element 4. The delay element 4 can be integrated into the optical wedge configuration 5. The analyzing device 10 and the polarizing device 3 can be replaced with a polarizing beam splitter. Finally, with the help of an end mirror (17, Fig 5) in combination with the retroreflector, the light beam can be projected a total of four times through the optical wedge configuration and the delay element (Fig. 5).

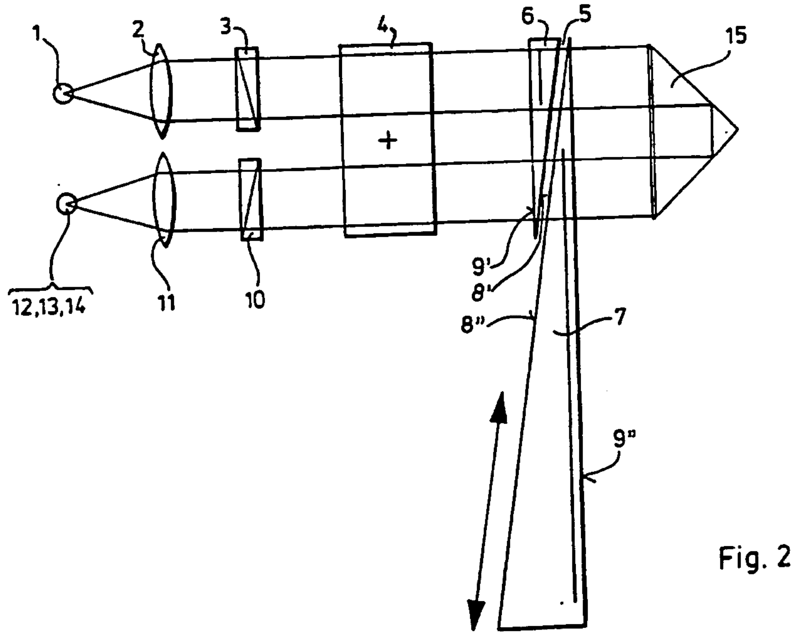

Fig. 2

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Fourier-Spectrometer

Background of the Invention

The invention concerns a Fourier spectrometer with an amplitude splitting polarization interferometer comprising the following components:

- a polarizing device for the linear polarization of a parallel light beam from a light source incident upon the interferometer;

- a birefringent delay element to split the linearly polarized light beam into an ordinary and an extraordinary ray each with the same propagation direction as that of the linearly polarized light beam;

- an optical wedge configuration consisting of birefringent material comprising two wedges which are moveable with respect to each other, whereby the two wedges are so arranged that their hypotenuse surfaces directly border on another, and the long surfaces opposite the hypotenuses have their faces plane-parallel to another and perpendicular to the propagation direction of the light in the interferometer, whereby at least one of the optical wedges is movable in a direction parallel to its hypotenuse surface in such a way that the relative distance between the plane parallel outer surfaces can be varied and whereby

the optical axes of at least one optical wedge are rotated by 90 degrees relative to the optical axis of the delay element and

- an analyzing device with a polarization plane rotated by a preset angle α relative to that of the polarizing device about the direction of the light beam exiting the optical wedge configuration.

Such a Fourier spectrometer is available from the Company TECAN AG from Switzerland under the label FT-NIR 4010.

The heart of a Fourier spectrometer is an amplitude splitting interferometer, classically not a polarization interferometer but a Michelson Interferometer, with which a parallel light beam from a light source is incident at an angle of 45 degrees on a semitransparent beam splitter which partially transmits the beam in a forward direction and partially reflects the beam in a perpendicular direction. Both partial beams are each reflected back onto the beam splitter by a planar mirror located perpendicular to their optical path. One of the two mirrors is stationary while the other can be displaced along the optical axis of the respective partial beam so that the optical path length traversed by this partial beam between the beam splitter and the mirror can be varied. The partial beams join together again at the beam splitter and interfer with each other to produce a light beam whose amplitude modulation depends on the position of

the movable mirror, and said amplitude modulated light beam leaves the interferometer in a direction perpendicular to the incident light beam emanating from the light source and is either directly introduced into a detector or first penetrates through a sample introduced into the optical path. The Fourier transform of the interferogram is formed from the detector signal with the help of a computer and represents a complete optical spectrum of the source, the instrument (interferometer), and, if applicable, the sample.

A substantial disadvantage of the Michelson interferometer is the precision required in guiding the movable interferometer mirror. In an interferometer available from the company Analect in Irvine/California and offered under the label "Transept", a significantly increased guiding unpreciseness can be tolerated in that the beam splitter utilizes a configuration comprising a movable and a fixed optical wedge made from transparent materials. By displacing the optical wedge, the optical path length traversed by the partial beam in the "moving" arm of the two armed interferometer is varied. By guiding the light through material with a high index of refraction, optical path length differences are produced between the two arms of the interferometer.

However, the two arm interferometer configuration still has the disadvantage that different thermal changes, by way of example, expansions of the optical elements in the two arms can lead to a serious

disalignment of the interferometer during the measurement.

This disadvantage does not occur in the above mentioned configuration offered by the company TECAN AG in accordance with the generic part of the main claim since this configuration does not exhibit a second arm which must be compensated with respect to a first arm, rather both partial beams pass through the optical elements of the interferometer at the same position and, therefore, a difference between two spatially separated partial beams cannot occur.

The changes in the optical path length differences in this configuration are, however, significantly limited by the maximum possible difference in the indices of refraction of the materials in the two optical wedges which, in turn, also limits the resolution capabilities of the spectrometer. Furthermore, in this construction scheme there are stringent requirements on the planar parallelness of the long outer surfaces opposite the hypotenuses of the two optical wedges, and, moreover, angle errors or deviations in the beam direction from the direction perpendicular to these outer surfaces, by way of example, through a finite divergence of the beam or due to tilted adjustment of the beam axis lead to significant disruptions in the interference pattern. Likewise, errors in the motion of the optical wedge moving along the hypotenuse surfaces have negative consequences.

The Fourier spectrometer in Fig. 1 is part of prior

art and is, as mentioned above, available from the Swiss Company TECAN AG. Light emanating from a, in general, wide-band light source 1 is formed in a first collimator configuration 2, represented here as a lens, into a parallel light beam which traverses an interferometer. The interferometer consists of a polarizing device 3, a delay element 4, a birefringent optical wedge configuration 5 consisting of a fixed optical wedge 6 and a movable optical wedge 7, whereby both wedges are so arranged that their hypotenuse surfaces 8', 8'' directly border on each other and the long outer surfaces (9',9'') opposite the hypotenuses are plane-parallel to another and arranged perpendicular to the propagation direction of the light in the interferometer, whereby the moving optical wedge is movable parallel to its hypotenuse surface 8'' in such a manner that the relative distance between the two plane parallel outer surfaces 9', 9'' can be varied, as well as an analyzer device 10. The light beam from the first collimator configuration 2 enters into the interferometer and is linearly polarized in polarizing device 3. When the angular position of the transmitting orientation of the polarizing device 3, in a plane perpendicular to the axis of the parallel light beam, is defined to be 45 degrees, then the subsequent delay element 4, which usually consists of a birefringent plane-parallel plate, has its optical axes so oriented relative to the polarizing device 3 that the parallel light beam penetrating perpendicularly through the delay element 4 is split into an ordinary and an extraordinary ray with each having the same propagation direction, that is to

say, into two linearly polarized portions, whose planes of oscillation assume the values 0 degrees and 90 degrees respectively in the plane perpendicular to the beam axis. Since the two beam components have different light velocities in the delay element 4, the parallel light beam exiting delay element 4 is not necessarily linearly polarized, rather in general, is elliptically or possibly circularly polarized. The light beam is incident upon the optical wedge configuration 5, whereby it penetrates perpendicularly through the plane parallel long outer surfaces 9', 9'' opposite the hypotenuses of the fixed optical wedge 6 and the larger movable optical wedge 7, respectively. The optical axes of the optical wedge configuration 5 are rotated by 90 degrees about the axis of the light beam relative to the optical axes of the delay element 4. By moving the movable optical wedge 7 along its hypotenuse surface 8'', it is possible to vary the optical thickness of the optical wedge configuration 5 in such a manner that it is equal to the optical thickness of the delay element 4 and thereby compensates for the effect of the splitting of the initially linearly polarized beam into two, with respect to each other, perpendicularly polarized components of differing travel times. In this special configuration, a parallel light beam leaves the optical wedge configuration 5 at an linearly polarized angle of 45 degrees and then is incident upon an analyzer device 10 whose transmission orientation assumes an angular value of -45 degrees relative to the plane perpendicular to the axis of the light beam so that, in this case, the light beam

is extinguished in the analyzer device. By moving the movable optical wedge 7, the optical thickness of the optical wedge configuration 5 relative to the optical thickness of the delay element 4 can be arbitrarily changed so that the parallel light beam exiting from the optical wedge configuration 5 is, in general, not linearly polarized at an angle of 45 degrees, and therefore, at least a portion of the light beam can traverse the analyzer device 10 and be incident upon a second collimator configuration 11 where the light beam is focussed onto an sample 12 and, finally, by means of lens 13, onto a detector 14. Here the light signals of the interferogram are received and passed on to a computer for Fourier transformation.

Although the interferometer configuration of prior art described above is mechanically compacter and more robust than the classical Michelson interferometer, stringent conditions for the precision with which the plane parallelness of the long outer surfaces 9', 9'' of the optical wedge configuration 5 are, however, necessary. Furthermore, the maximum possible path difference between the partial beams is limited by the difference between the indices of refraction of the optical wedge materials.

Summary of the Invention

The object of the present invention is therefore to further improve a Fourier spectrometer of the above mentioned kind in that the requirements on the

angular precision of the optical components, in particular the optical wedge configuration, can be substantially reduced without loss of resolution capability or measuring accuracy, in that dynamic errors in the motion of the movable optical wedge have less disruptive effects, and in that the optical path difference between the two partial beams in the interferometer and, thereby, the resolution capability of the Fourier spectrometer is increased.

This object is achieved in accordance with the invention in that, viewed in the direction of propagation of the light beam first passing through the optical wedge configuration, a retro-reflector is provided for after the optical wedge configuration.

Since the light beam is reflected from the retro-reflector, said light beam passes through the optical wedge configuration at least twice which, in turn, doubles the optical path length difference and, thereby, the optical resolution capability of the Fourier spectrometer. Small angular deviations of the optical path in the optical wedge are self-compensating in that they occur oppositely in the return path of the retro-reflected beam passing through the optical wedge and therefore, in effect, are cancelled. For the same reason dynamic errors in the motion of the moving optical wedge are self-compensating. In general, in the configuration according to the invention, the requirements on the angular precision of the optical components can be reduced approximately by one order of magnitude. A further advantage is that the spectrometer is only

half as long in its lengthwise extension as the configuration according to prior art.

Also, however, known in the art from publication "Journal of Scientific Instruments", Vol. 37, August 1960, Pages 278 through to 281, is a configuration with which a beam is guided through an optical wedge arrangement, reflected back upon itself, and once again guided through the optical wedge configuration. However, in this apparatus one is not dealing with a spectrometer, rather simply with a modification of a Babinet-compensator with which, through the displacement of the optical wedges, optical path differences of monochromatic light of only the order of one or two wave lengths are produced, with the sample being located between the polarizer and the analyzer, while in a spectrometer path differences of several thousand wave lengths must be produced. Optical elements are introduced into the optical path of such a compensator to examine their birenfringement properties as well as for optical checks of inaccuracies in components. A spectral analysis is not possible with such an arrangement.

In a preferred embodiment of the Fourier spectrometer according to the invention, the angle α by which the analyzer configuration is rotated with respect to the polarizer configuration assumes a value of 90 degrees. Adjustment of the configuration then takes place with the transmitted light at a minimum which allows for the greatest possible adjustment precision.

In another embodiment, the optical wedge configuration is comprised of a fixed and a movable optical wedge. Adjustment is substantially simplified with a fixed optical wedge compared to the configuration with two moving optical wedges.

In an embodiment of the Fourier spectrometer according to the invention, the delay element is part of the optical wedge configuration, in particular integrated into the fixed optical wedge, whereby the number of components in the interferometer and thereby the number of possible sources of error is reduced and the entire spectrometer is more compact.

In a further embodiment, the polarizer and the analyzer are formed by a polarizing beam splitter, the retro-reflector being arranged in such a manner, that the light beam last exiting from the optical wedge configuration runs coaxially and in the opposite direction to the beam first entering into the optical wedge configuration, is incident upon the back side of the polarizing beam splitter and, finally, is introduced into the sample-detector configuration of the Fourier spectrometer. In this embodiment, the number of linearly polarizing optical instruments is reduced from two to one so that the possible sources of error associated with the individual components are even further reduced and the overall construction is more compact.

In a preferred improvement of this embodiment the retro-reflector is arranged in such a manner that the light beam first exiting from the retro-reflector is

displaced in a parallel direction relative to the light beam first incident on the retro-reflector, and that, viewed in the propagation direction of the light beam first leaving the retro-reflector, a mirror is arranged behind the optical wedge configuration which reflects the light back into itself. In this manner, the light beam is caused to pass a total of four times through the optical configuration which, in turn, leads to a fourfold increase in the optical path difference compared to the generic portion of claim 1 and, thereby, to a fourfold increase in the resolution capability.

The retro-reflector can, in certain embodiments of the invention, be a corner cube or can also be configured from a cat's eye containing either a planar mirror and a concave mirror, or a planar mirror and a convex lens. Of primary importance is that the beam is reflected with point-symmetry.

In a preferred embodiment, an optical fiber configuration is provided for which guides the light beam exiting from the interferometer to a sample arranged outside of the Fourier spectrometer and the light emanating from the sample into the Fourier spectrometer detector device. Therefore the sample may be arranged spatially removed from the Fourier spectrometer, thus no direct mechanical contact with the spectrometer takes place while changing samples, which, in turn, further minimizes the danger of an unintentional disalignment of the spectrometer and opens up the possibility of undertaking spectral analysis at locations in which a Fourier

spectrometer, for reasons of spatial considerations or other reasons, cannot be installed.

The Fourier spectrometer in accordance with the invention can be operated in all optical wavelength regions in which the materials utilized are transparent and birefringent, in particular however, with a light source which emits wide-band light in the near infrared. In this manner, it is in particular possible to take vibration and rotation spectra of molecules in liquids.

The invention is now further described and explained by means of the embodiment represented in the drawing. The features which can be derived from the drawing and the description can also be applied in other embodiments of the invention either individually or collectively in arbitrary combinations.

<u>Brief Description of the Drawings</u>

Fig. 2 is a scheme of a spectrometer according to the invention;

Fig. 3 is a scheme of a spectrometer according to the invention with a delay element integrated into the optical wedge configuration;

Fig. 4 is a scheme of a spectrometer according to the invention with the delay element integrated into the optical wedge configuration and with a polarizing

beam splitter;

Fig. 5 is a scheme of a spectrometer according to the invention with a delay element integrated into the optical wedge configuration, with a polarizing beam splitter, and a mirror retro-reflector configuration which permits a fourfold passage of the light beam through the optical wedge configuration;

Fig. 6a is a scheme of a cat's eye configuration with planar mirror and concave reflector;

Fig. 6b is a scheme of a cat's eye configuration with planar mirror and convex lens; and

Fig. 7 is a scheme of a configuration for guiding light into and out of the sample.

Detailed Description of the Preferred Embodiment

The two disadvantages mentioned above in connection with Fig. 1 can be avoided in the Fourier spectrometer according to the invention. Reference numerals corresponding to Fig. 1 denote the same or similar components. In the Fourier spectrometer according to the invention, as viewed in the propagation direction of the light beam first penetrating through the optical wedge configuration 5, a retro-reflector 15 is provided for behind the optical wedge configuration as, by way of example, shown in Fig. 2. Due to the fact that the light beam

penetrates at least twice through the delay element 4 and the optical wedge configuration 5, a doubled optical path length difference compared to the linear configuration of Fig. 1 results, and, thereby, a doubled resolution capability for the spectrometer. Small angular deviations of the light beam while penetrating through the delay element 4 and the optical wedge configuration 5 are self-compensating in that they occur in the opposite direction during the second passage through the corresponding optical elements and, therefore, in effect, are mutually cancelled. This is also the case for angular errors which occur in consequence of deviations from linearity in the motion of the moving optical wedge 7 along the hypotenuse surfaces 8', 8''. A further advantage of the configuration according to the invention is that it is only half as long as the linear configuration.

It is not entirely necessary that the optical wedge 6 be arranged in a fixed manner, rather it can also be movable relative to optical wedge 7. The preferred relative angular orientation α of the analyzing device 10 relative to the polarizer device 3 assumes a value of 90 degrees, since an optical adjustment is most simply and most accurately achieved when the light penetrating through the configuration is at a minimum. The relative angle α can also, however, assume a value of 0 degrees so that the quantity of light penetrating through is maximum, or an arbitrary preset intermediate value when, in this fashion, it is desireable to increase the light yield in the detector 4.

An even more compact embodiment is shown in Fig. 3 in which the delay element 4 is integrated into the optical wedge configuration 5, in particular, into the fixed optical wedge 6. The orientation of the optical axes of the fixed optical wedge 6 must, in this configuration, be rotated by 90 degrees about the axis of the light beam relative to the orientation of the optical axes of the moving optical wedge 7.

A further savings in optical components and in spectrometer size is given by the embodiment according to Fig. 4 where the polarizing device 3 and the analyzing device 10 are replaced by one single polarizing beam splitter 16. In this embodiment, the retro-reflector 15 is arranged in such a manner that the light beam finally exiting from the optical wedge configuration 5 runs coaxially with and in an opposite direction to the light beam entering the optical wedge configuration 5, that is to say, is reflected back into itself. In this fashion, it is also possible to shorten the lateral dimensions of the interferometer.

Fig. 5 shows a particularly preferred embodiment of the invention in which the light beam initially penetrates the optical wedge configuration 5, with integrated delay element 4, and is incident upon the retro-reflector 15 wherefrom it is projected through the optical wedge configuration 5 onto a mirror 17, said mirror 17 reflecting the beam back into itself and through the optical wedge configuration 5 onto

the retro-reflector 15 which once again projects the light, in a parallel-displaced direction, through the optical wedge configuration 5 onto the polarizing beam splitter 16. In this manner, the optical wedge configuration 5 with the integrated delay element 4 is traversed a total of 4 times by the light beam resulting in a fourfold increase in the optical path difference compared to the linear configuration according to Fig. 1 and, thereby, in a fourfold increase in the resolution capability of the interferometer.

In embodiments of the invention, the retro-reflector 15 can be a corner cube. It can also, however, comprise a cat's eye configuration which, as shown in Fig. 6a, contains a concave mirror 19 which projects the light beam onto a planar mirror 18 which, for its part, reflects the beam back onto the concave mirror 19 where it is reflected antiparallel to its original direction or, as shown in Fig. 6b, can be configured from a convex lens 20 and a planar mirror 18.

The sample 12 can, as shown in Fig. 1, be arranged linearly between the second collimator configuration 11 and a lens 13 which focusses the light from the sample onto a detector 14. Another possibility for the sample-detector configuration is shown in Fig. 7 where the light leaving the second collimator configuration 11 is guided out of the interferometer with the aid of a optical fiber configuration 21 to the sample 12 and therefrom with the optical fiber configuration 21 is focussed into the detector 14 via a lens 13. This configuration has the advantage that

the sample can be arranged spatially removed from and outside of the Fourier spectrometer.

The reference numerals in the patent claims are not a restriction but shall facilitate their understanding.

Claims

1. Fourier spectrometer with an amplitude splitting polarization interferometer comprising the following components:

- a polarizing device (3) for the linear polarization of a parallel light beam incident into the interferometer from a light source (1);

- a birefringent delay means (4) for the splitting of the linearly polarized light beam into an ordinary and an extraordinary ray with each having the same propagation direction as that of the linearly polarized light beam;

- an optical wedge configuration (5) of birefringent material, comprised of two optical wedges (6,7) which are movable with respect to each other, whereby the two optical wedges (6,7) are so arranged that their hypotenuse surfaces (8', 8'') directly border on each other, the long outer surfaces (9', 9'') opposite the hypotenuses are each plane-parallel to each other and are oriented perpendicular to the propagation direction of the light in the interferometer, whereby at least one of the optical wedges (6,7) is movable parallel to its hypotenuse surface (8'') in such a manner that the relative distance between the plane-parallel outer surfaces (9', 9'') can be varied, and whereby the optical axes of at least one of the movable optical wedges

(6,7) are rotated by 90 degrees relative to the optical axes of the delay means (4) and

- an analyzing device (10) with a polarization plane rotated by a preset angle α relative to the polarizing device (3) about the direction of the light beam exiting the optical wedge configuration (5),

characterized in that,

as viewed in the propagation direction of the light beam first penetrating through the optical wedge configuration (5), a retro-reflector (15) is provided for behind the optical wedge configuration (5).

2. Fourier spectrometer according to claim 1, characterized in that the angle α assumes a value of 90 degrees.

3. Fourier spectrometer according to claim 1 or 2, characterized in that the optical wedge configuration (5) consists of a fixed wedge (6) and a movable wedge (7).

4. Fourier spectrometer according to claim 1 or 3, characterized in that the delay means (4) is integrated into the optical wedge configuration (5).

5. Fourier spectrometer according to one of the preceding claims, characterized in that the

polarizing device (3) and the analyzing device (10) are formed by a polarizing beam splitter (16) and the retro-reflector (15) is arranged in such a way that the light beam last exiting from the optical wedge configuration (5) runs coaxially with and in the opposite direction to the light beam first incident upon the optical configuration (5).

6. Fourier spectrometer according to claim 5, characterized in that the retro-reflector (15) is arranged in such a way that the light beam first leaving the retro-reflector (15) is displaced in parallel relative to the light beam first entering and that, as viewed in the propagation direction of the light beam first leaving the retro-reflector (15), a mirror (17) is arranged behind the optical wedge configuration (5) which reflects the light back into itself.

7. Fourier spectrometer according to one of the preceding claims, characterized in that the retro-reflector (15) is a corner cube.

8. Fourier spectrometer according to one of the claims 1 through 6, characterized in that the retro-reflector (15) is a cat's eye consisting of a planar mirror (18) and a concave mirror (19).

9. Fourier spectrometer according to one of the claims 1 through 6, characterized in that the retro-reflector (15) is a cat's eye configuration consisting of a planar mirror (18) and a convex

lens (20).

10. Fourier spectrometer according to one of the preceding claims, characterized in that an optical fiber configuration (21) is provided for which guides the light beam leaving the interferometer to a sample (12) arranged outside of the Fourier spectrometer and guides the light beam leaving the sample (12) to a detector device (14) of the Fourier spectrometer.

11. Fourier spectrometer according to one of the preceding claims, characterized in that the light source (1) emits wide-band light in the near infrared.

12. Fourier spectrometer substantially as described with reference to the drawings.

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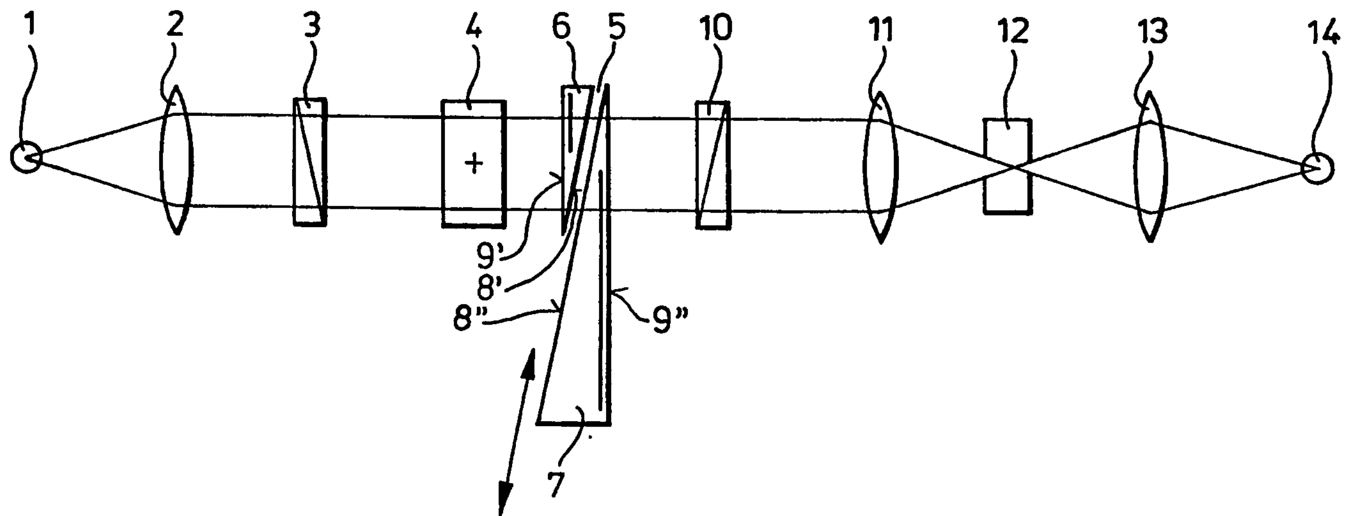

Fig.1

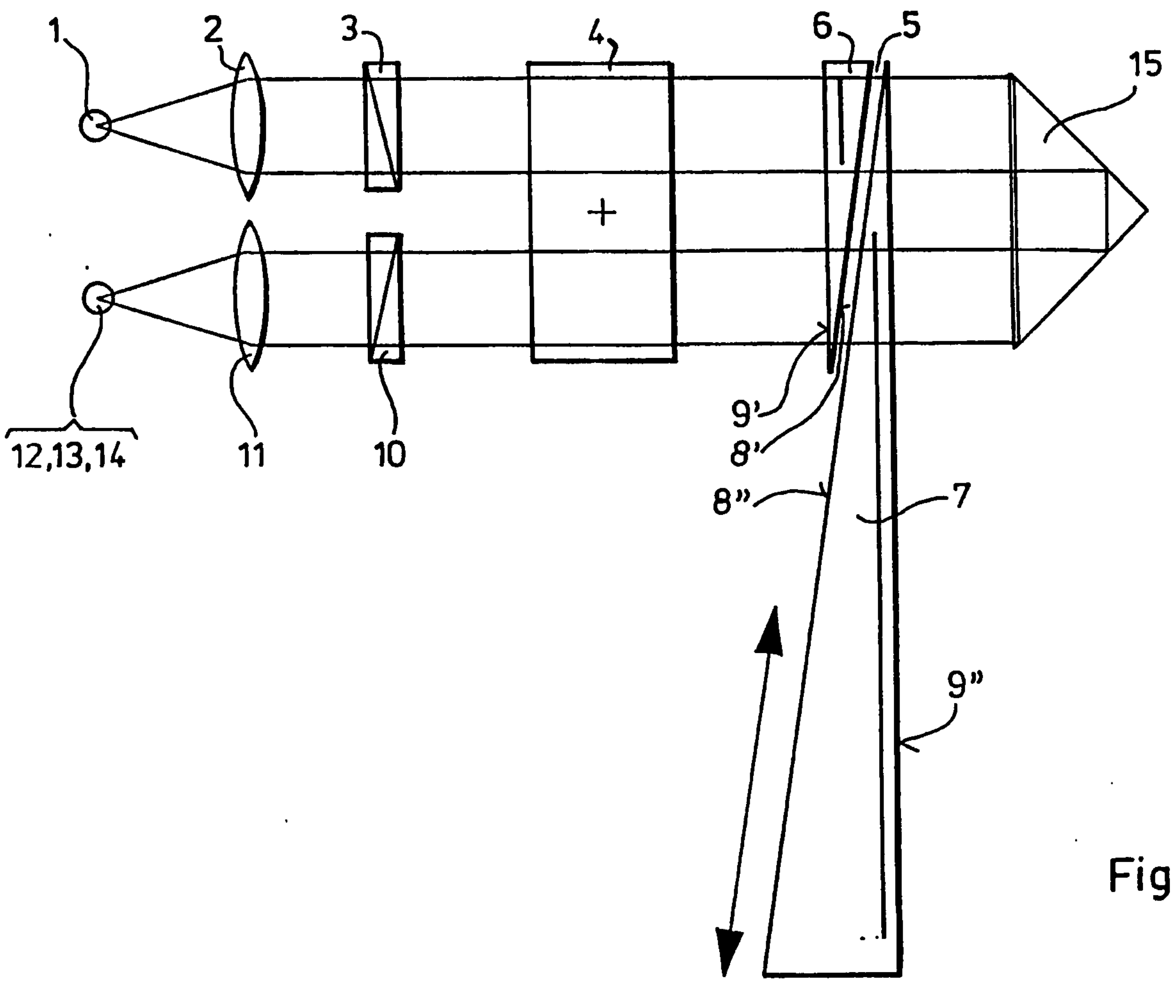

Fig. 2

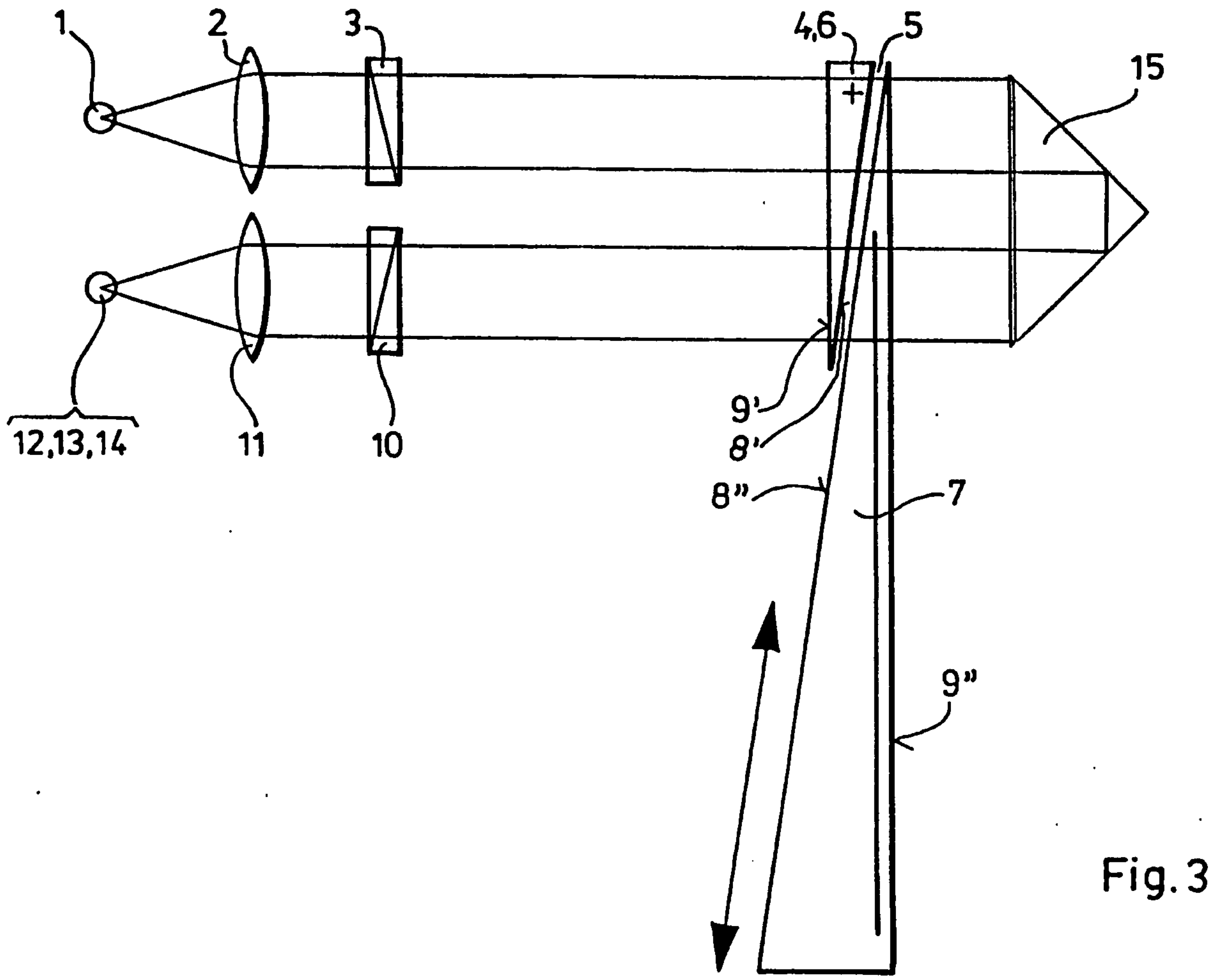

Fig. 3

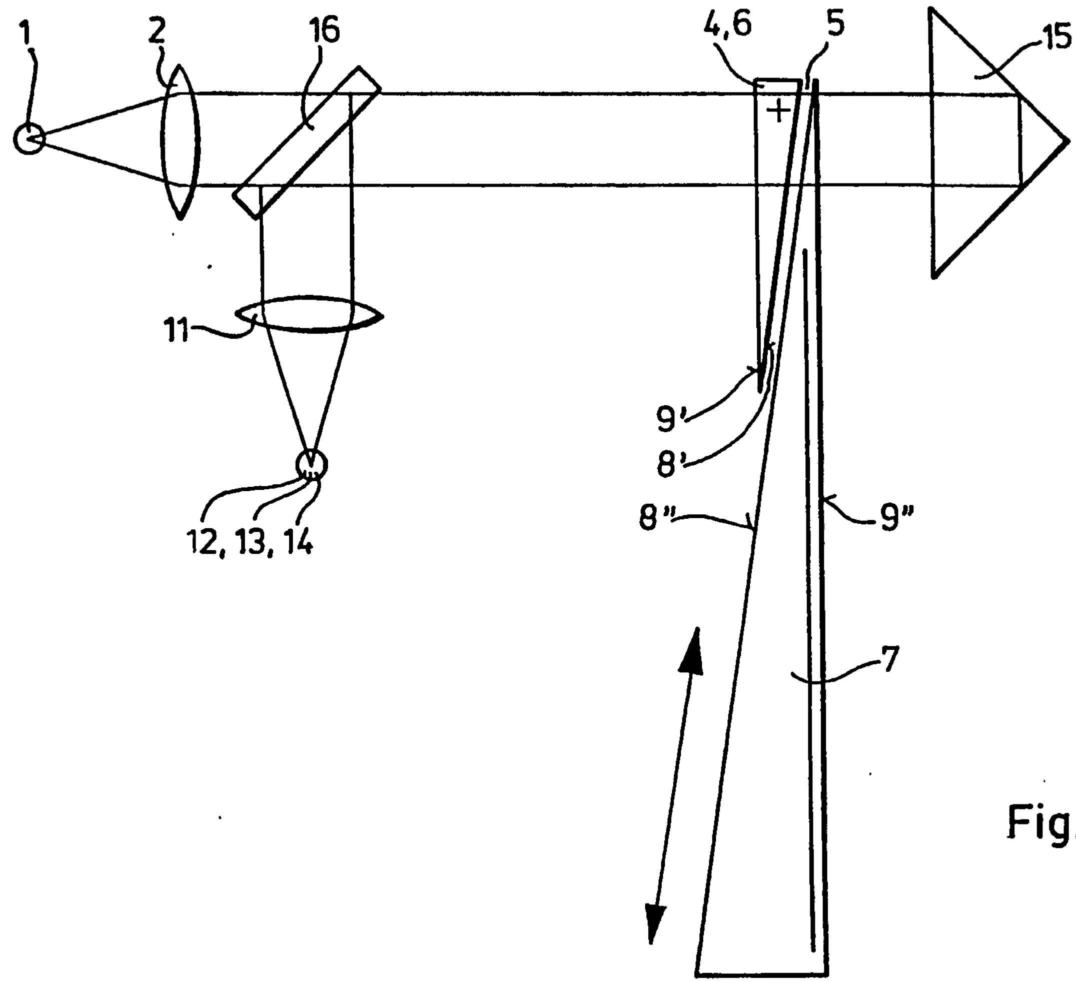

Fig. 4

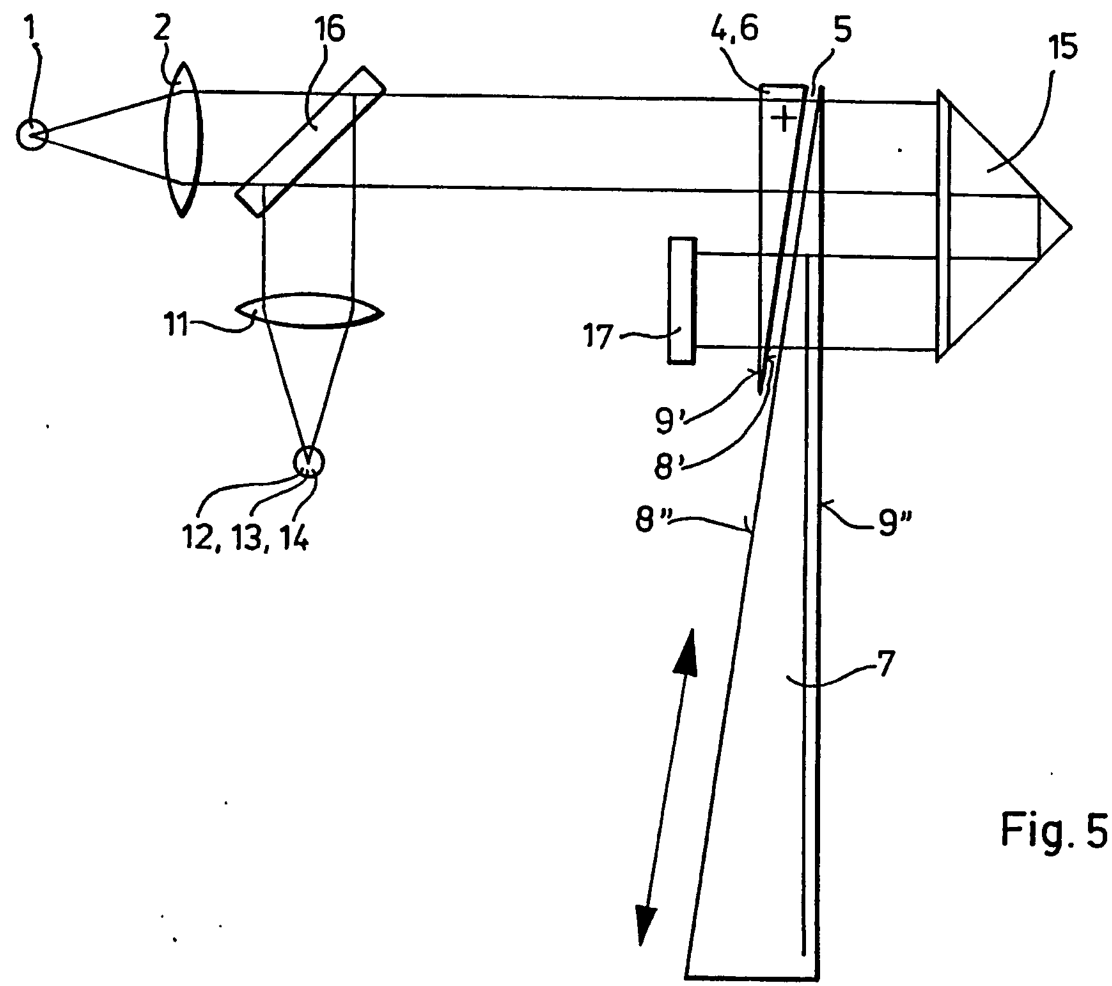

Fig. 5

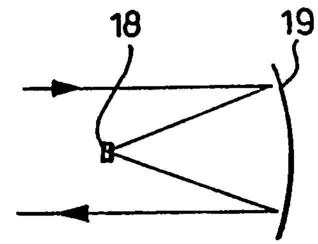

Fig 6a

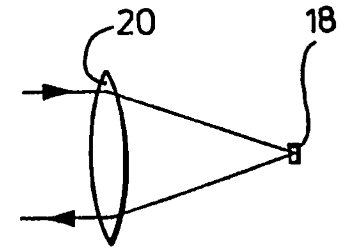

Fig. 6b

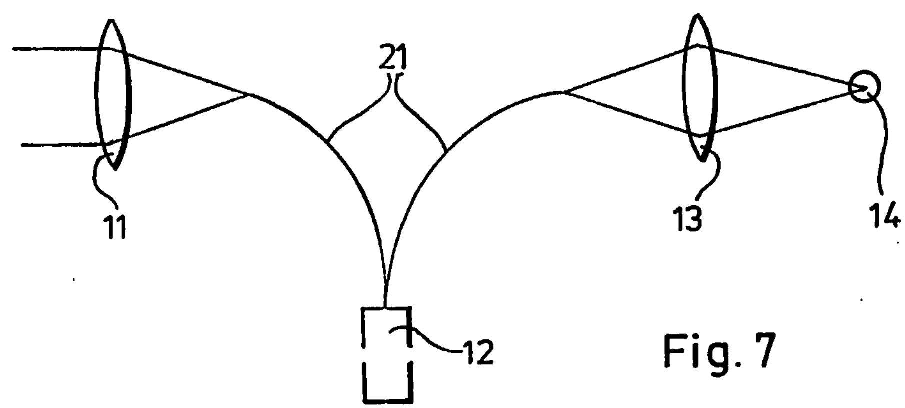

Fig. 7